INTEGRATING APEX OUTPUT FOR CULTIVATED CROPLAND WITH SWAT SIMULATION FOR REGIONAL MODELING

X. Wang, N. Kannan, C. Santhi, S. R. Potter, J. R. Williams, J. G. Arnold

ABSTRACT. *The purpose of the Conservation Effects Assessment Project (CEAP) cropland national assessment is to quantify the environmental benefits of conservation programs at the regional and national levels, which include both onsite and instream water quality benefits. Modeling is an effective tool for environmental assessment at the regional and national scale due to the complexities in nature at this scale. Two simulation models, the Agricultural Policy Environmental eXtender (APEX) and the Soil and Water Assessment Tool (SWAT), were used for the CEAP cropland national assessment. A subset of National Resources Inventory (NRI) sample points was selected to serve as "representative fields" for the CEAP cropland survey to determine conservation practices currently in use. The NRI-CEAP points for cultivated cropland were simulated using APEX. The APEX results were aggregated and combined with modeling results from SWAT for uncultivated land uses. The combined modeling results at 8-digit watershed outlets were routed downstream in SWAT for estimating the offsite effects of conservation practices. The regional modeling involved three major steps: APEX setup for simulating conservation practices, calibration of water yield at the 8-digit watershed level (1961-1990), and development of sediment delivery ratios (SDR) for transporting sediment from cultivated cropland and uncultivated land to the 8-digit watershed outlet before combining model outputs for further routing downstream. The objective of this article is to address the use of APEX to model CEAP cultivated cropland, APEX simulation of conservation practices, and SDR development and to test the combined modeling of flow and sediment yield for the upper Mississippi River basin. Simulated annual and monthly flows at key gauging stations along the river basin and annual sediment yields at Valley City and Alton/Grafton, Illinois, were compared with observed values. Test results are promising for using the combined modeling systems for large-scale studies and for performing scenario analyses to evaluate conservation practices. The limitations of this national modeling include the uncertainties associated with data (channel dimensions, conditions of structural practices) and the inability to account for streambank and channel erosion at the 8-digit watershed level. Therefore, while using absolute predictions for individual scenarios, consideration should be given to various uncertainties. Both data updating and the development of an enhanced SWAT model with streambank/channel erosion components and particle size distribution are underway for reducing the level of uncertainty in future national-scale modeling efforts.*

Keywords. *APEX, Conservation practice, Mississippi River basin, Sediment delivery ratio, SWAT, Water yield.*

Conservation practices are designed to reduce the loss of soil, nutrients, or pesticides in order for farmlands to remain productive, improve instream water quality, and enhance the quality of agro-ecosystems. The assessment of conservation practices allows policy-makers to make informed decisions for designing new conservation programs and to improve the implementation of existing programs. Field studies and modeling approaches have both been used to evaluate the effects of conservation practices (Sharpley and Smith, 1994; Bottcher et al., 1995; Sharpley et al., 1996; Edwards et al., 1997; Bishop et al., 2005; Chen et al., 2000; Vache et al., 2002; Gitau et al., 2005). While extensive literature exists that describes plot- or field-scale conservation practices (King et al., 1996; Chow et al., 1999; Wang et al., 2008; Yin et al., 2009), research results from plot- and field-scale studies do not capture the complexities and interactions of conservation practices within a watershed. Moreover, the effects of conservation programs have not previously been quantified at the national or regional scale.

The USDA Natural Resources Conservation Service (NRCS) and Agricultural Research Service (ARS) are working together on the Conservation Effects Assessment Project (CEAP) (Mausbach and Dedrick, 2004). The purpose of the CEAP cropland national assessment component is to quantify the environmental benefits of conservation practices at regional and national levels, which include both onsite and instream water quality benefits. This process involves developing a set of individual farm field simulations based on an extensive farming practice surveys developed by NRCS and administered by the National Agricultural Statistics Service (NASS). The surveys represent approximately 20,000 different farmers in 2003-2006 on cultivated

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The authors are **Xiuying Wang, ASABE Member,** Research Assistant Professor, **Narayanan Kannan, ASABE Member,** Assistant Research Scientist, **Chinnasamy Santhi,** Associate Research Scientist, **Jimmy R. Williams,** Senior Research Scientist, Blackland Research and Extension Center, Texas AgriLife Research, Texas A&M University, Temple, Texas; **Steven R. Potter,** Graduate Student, Water Management and Hydrologic Sciences Program, Texas A&M University, College Station, Texas; and **Jeffrey G. Arnold, ASABE Member,** Supervisory Agricultural Engineer, USDA-ARS Grassland Soil and Water Research Laboratory, Temple, Texas. **Corresponding author:** Xiuying Wang, Blackland Research and Extension Center, Texas AgriLife Research, 720 E. Blackland Rd., Temple, TX 76502; phone: 254-774-6105; e-mail: swang@brc.tamus.edu.

cropland and several thousand more NRI points representing land enrolled in the Conservation Reserve Program (CRP) general signup. The environmental effects to be estimated include losses of nitrogen and phosphorus, soil carbon changes from the farm field, and instream water quality at regional and national levels. The effects of conservation practices can be estimated based on the different model outputs between two scenarios: the current conservation condition scenario, and an alternative scenario with no conservation practices in use. Detailed simulation of conservation practices and/or complex agronomic systems is necessary in order to realistically report the conservation effects.

The Agricultural Policy Environmental eXtender (APEX; Williams and Izaurralde, 2006) was coupled with a regional water quality model, the Hydrologic Unit Model for the United States / Soil and Water Assessment Tool (HUMUS/SWAT; Arnold et al., 1998; Srinivasan et al., 1998), for the CEAP cropland national assessment study. Applications of the combined APEX and SWAT model have been reported by Saleh et al. (2000, 2003), Osei et al. (2000), Saleh and Gallego (2007), and Gassman et al. (2001, 2002). The SWAPP-SWAT/APEX program (Saleh and Gallego, 2007) and ArcAPEX/ArcSWAT (Tuppad et al., 2009) interfaces have been developed to facilitate the integration of APEX and SWAT to strengthen the overall modeling capacities. These GIS-based user interfaces integrate topographic, land use, soil, and weather spatial datasets with built-in APEX and/or SWAT parameters. The interfaces allow users to select the APEX model for detailed simulation of farms or small subwatersheds with complex agronomic systems and the SWAT model for subwatersheds with more homogeneous and less complex agricultural systems, as well as non-agricultural landscapes. The SWAT model is also used for integrating constituent contributions from all subwatersheds and simulating instream channel processes.

For the CEAP cropland national assessment, it is not realistic to use GIS-based interfaces in which a digital elevation model (DEM) would be used to delineate the whole nation; however, the HUMUS/SWAT watershed modeling framework was followed in CEAP. Within the HUMUS framework, each water resource region (major river basin) is treated as a watershed, and each U.S. Geological Survey (USGS) delineated 8-digit watershed is treated as a subwatershed for use in SWAT modeling. HUMUS includes databases on land use, soils, weather data, and point-source pollutants that are used with SWAT to simulate the transport of water and potential pollutants from the land to receiving streams, and routes the flow downstream to the next watershed and ultimately to the estuaries and oceans (USDA-NRCS, 2010). The HUMUS system is updated with recently available databases (2001 National Land Cover Data and weather data) and with the SWAT model (Santhi et al., 2005; Di Luzio et al., 2008), as well as with the cultivated cropland and CRP land assigned for using the APEX model.

For regional modeling setup, major steps were taken to integrate APEX results with SWAT regional simulation, including: (1) develop a modeling approach to represent and simulate various conservation practices using APEX for cultivated cropland, (2) calibrate water yield at each USGS-delineated 8-digit watershed and calibrate/validate streamflow at major river basin outlets to capture spatial variations and ensure temporal variability, and (3) develop sediment delivery ratios (SDR) for transporting sediment from cultivated cropland (simulated using APEX) and uncultivated land uses (simulated with SWAT) to the 8-digit watershed outlet before the combined model outputs are further routed downstream. The objectives of this study were to: (1) briefly describe the APEX-SWAT CEAP cropland national assessment modeling framework and APEX simulation of conservation practices, (2) address delivery ratio development for transporting sediment from simulation units to 8-digit watershed outlets, and (3) calibrate/validate water yield and sediment yield for the upper Mississippi River basin (UMRB).

Materials and Methods

Study Area

The upper Mississippi River basin (UMRB) covers approximately 190,000 square miles, including large parts of Illinois, Iowa, Minnesota, Missouri, and Wisconsin and small areas of Indiana, Michigan, and South Dakota. The area is also referred to as Region 07 by the USGS at a 2-digit watershed scale. The major rivers that flow to the Mississippi River include the Minnesota River, Iowa River, and Illinois River (fig. 1). The region is comprised of 131 USGS-delineated 8-digit watersheds. The average annual rainfall (1960-2006) in the 8-digit watersheds ranges from 580 to 1190 mm. Cultivated cropland comprises about 50% of the UMRB land use, and approximately 2% of the land is enrolled in the CRP general signup. Within each 8-digit watershed, the percentage of cultivated cropland and CRP area ranges from 0% to 89% (fig. 2a). Forest land (about 18%) is the second most common land use, mostly in the northern part of the UMRB (USDA-NRCS, 2010).

APEX and SWAT

The APEX model is an integrated dynamic tool that is capable of simulating extensive land management strategies, such as nutrient management practices, tillage operations, and alternative cropping systems on the field, farm, or small watershed scale. It can be configured to simulate filter strip impacts on pollutant loss from upslope fields, intensive rotational grazing scenarios depicting movement of cows between paddocks, impacts of vegetated grassed waterways in combination with filter strip, land application of manure, as well as removal of manure from livestock feedlots or waste storage ponds (Gassman et al., 2010). APEX operates on a daily time step. A detailed theoretical description of APEX can be found in Williams and Izaurralde (2006).

The APEX model was selected for the CEAP field-level cropland modeling due to its flexibility and features. For example, field units within APEX have spatial relationships and can be routed at the field scale, which provides for physically based simulation of conservation practices such as filter strips, terraces, and waterways. In addition, the APEX crop growth component enables simulation of mixed stands with plant competition for light, water, and nutrients. APEX also simulates detailed management practices related to farm animal production, rotational grazing, and wind erosion. APEX enables dynamic soil layers associated with soil erosion and removal of eroded material, and it provides eight options (including RUSLE 2) for estimating water erosion. APEX simulates tillage with the functions for mixing

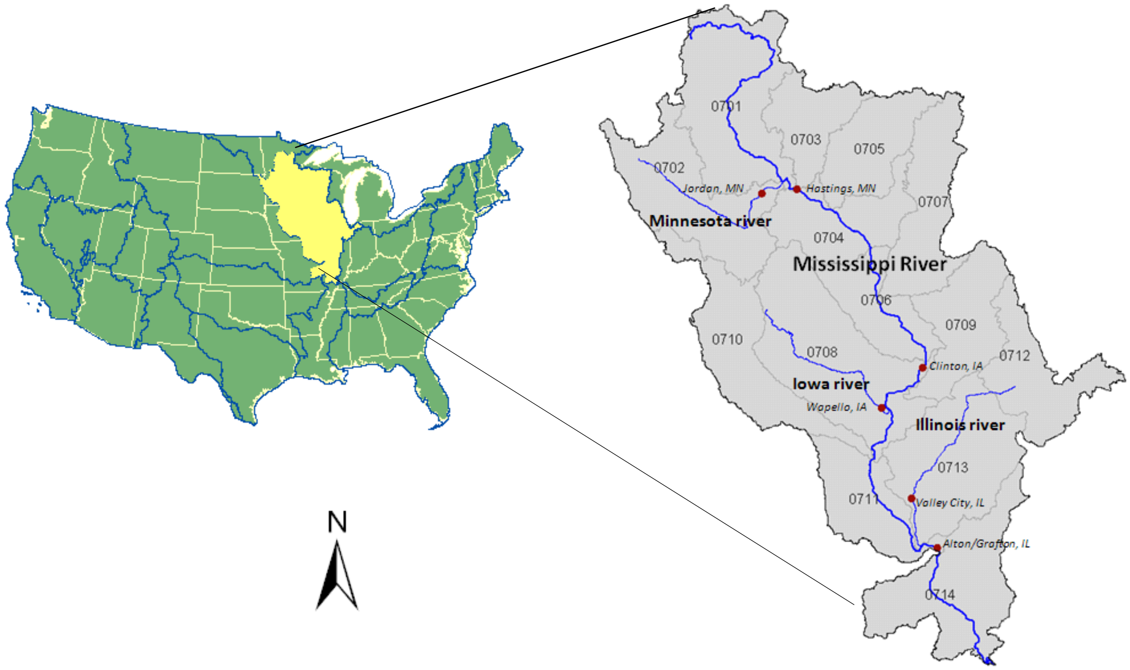
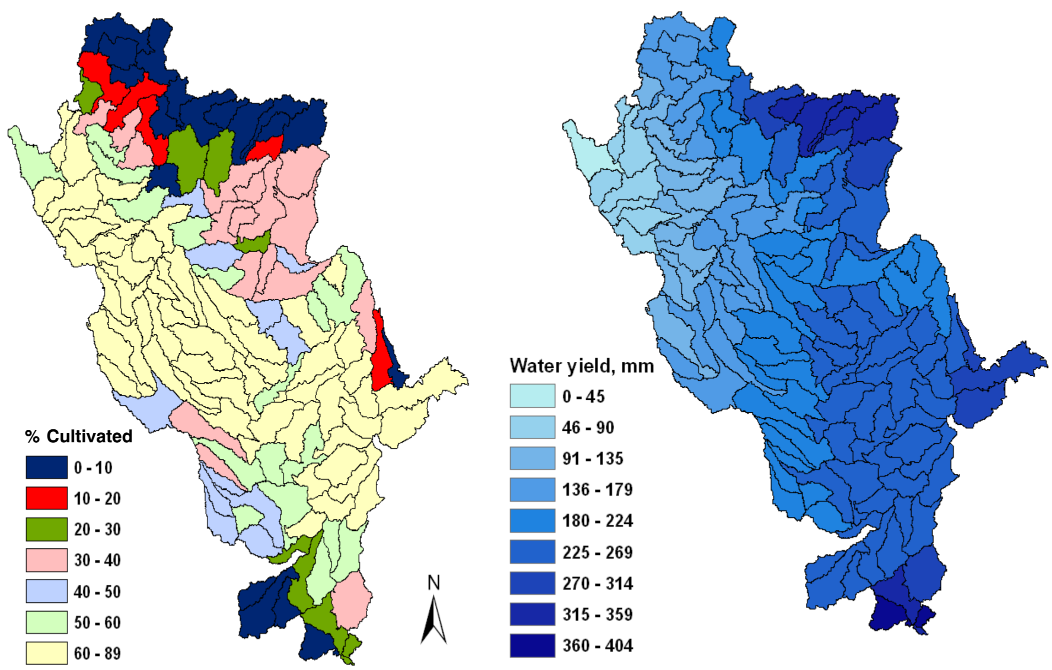


Figure 1. Locations of the upper Mississippi River basin and USGS gauging stations used for model evaluation.



(a) % cultivated cropland **(b) Observed water yield**

Figure 2. Percent cultivated cropland (a) and average annual water yield for 8-digit watersheds (b) in the upper Mississippi River basin.

nutrients and crop residue, converting standing residue to flat residue, changing bulk density and subsequent settling after tillage, and speeding mineralization. APEX features an improved soil carbon cycling routine that follows the Century model (Parton et al., 1987, 1993, 1994; Vitousek et al., 1994). APEX has also manure management with automatic application from a stockpile or a lagoon, and simulates manure erosion from feedlots and application fields.

The SWAT model is a basin-scale distributed hydrologic model. It was developed to quantify the impact of land management practices in large, complex catchments (Arnold et al., 1993). SWAT is capable of accepting output data from other simulation models. SWAT operates on a daily time step and allows a basin to be divided into subbasins based on topography to incorporate spatial details. Each subbasin is further divided into hydrological response units (HRUs), which are unique combinations of soil and land cover.

Individual HRUs are simulated independently, area weighted, and added for each subbasin and then routed through a stream network to the basin outlet. HRUs allow more spatial detail to be included by representing more land use and soil classifications in the landscape in a computationally efficient manner. The HUMUS project (Srinivasan et al., 1998) used SWAT to model 350 USGS 6-digit watersheds in the 18 major river basins in the U.S. The revised HUMUS/SWAT (Santhi et al., 2005) modeling framework with updated databases for the 18 major river basins was used for the CEAP cropland national assessment, in which the cultivated cropland and CRP land are simulated using the APEX model.

Statistical Sampling and Modeling Approach

Framework

The CEAP cropland component uses a sampling and modeling approach to estimate the benefits of conservation practices. Sampling is conducted for cropland fields in order to obtain a full representation of the diversity of cropping systems, resource concerns, farming activities, conservation practices, soils, climate, and other natural resource conditions on cultivated cropland. The APEX model was used for cropland simulation to estimate field-level benefits. The offsite benefits were assessed by integrating the cropland output from APEX with the HUMUS/SWAT model.

In the HUMUS/SWAT system, each major river basin (e.g., the UMRB) is treated as a watershed, each 8-digit watershed is treated as a subbasin or subwatershed, and unique combinations of soil and land cover (2001 National Land Cover Data) within each 8-digit watershed are treated as HRUs. The HRUs of uncultivated land use and land cover were simulated using SWAT, and the remaining cultivated cropland and CRP land were simulated using APEX.

The cultivated cropland may subdivided into multiple subareas (e.g., cropland with grass filter and riparian buffer, fig. 3). Management data for the cultivated cropland (crop rotation, tillage operation, nutrient and pesticide application, and conservation practices) were collected mainly through the CEAP cropland survey. The available data, their sources, and major structural conservation practices for APEX modeling are summarized in tables 1 and 2. Using this modeling framework, APEX can be implemented for more detailed simulation of cultivated cropland, while SWAT can be used for less complex uncultivated landscapes and for integrating runoff, sediment, nutrient, and pesticide contributions from all areas and point-source pollutants, as well as simulating instream channel processes.

Sampling and Integration

A subset of the 2002 and 2003 NRI sampling units was selected for the CEAP cropland survey. The sampling strategy developed for the farmer surveys included collecting survey data for 20,000 cropland sample sites over a four-year period (2003-2006). Sampling and data collection for 2003 and 2004 were focused on developing a good baseline for the most predominant cropping and conservation systems to ensure that credible statistical analyses could be made on a national basis for all U.S. cultivated cropland. Sampling and data collection for 2005 and 2006 were focused on obtaining data for areas and systems that are less extensive but usually more environmentally sensitive (vulnerable) and to obtain data on actual changes in conservation systems and practices that occurred due to implementation of 2002 Farm Bill provisions (Goebel, 2009).

For each NRI survey year, data were collected at both the segment level and point level. An estimation weight was attached to each record. Each of these created points was given an initial weight based on the area in the segment and the probability that the segment was included in the sample. Imputation (in statistics, substitution of some value for missing data, for example, using approximate Bayesian bootstrap to impute missing data) was used for unobserved

Table 1. Available data and their sources for APEX simulation of cultivated cropland.[a]

Data Type	Source[b]	Date	Description
Landscape	NRI	1997 or 2003	NRI point attribute data, including links to soil attribute data, slope and slope length, use indicators of conservation practices, and land use history.
Crop management	NRI-CEAP cropland survey	2003-2006	Crop rotation, including cover crops, fallow, multiple crops, and CRP vegetative cover; tillage, planting, and harvesting operations; fertilizer and manure management; and pesticide management.
Structural conservation practices	NRI, CEAP surveyed farmers, NRCS field office, and Farm Service Administration (CREP)	1997 or 2003 NRI and 2003-2006 CEAP survey	See table 2, Structural Conservation Practices column.
Soils	NASIS (USDA-NRCS 2007), Pre-NASIS Soils_5 database, NSSL, and NCSS laboratories	--	Layer depth, bulk density, organic carbon content, sand content, silt content, coarse fragment content, soil pH, soil albedo, soil hydrologic group, soil water content at wilting point, soil water content at field capacity, initial organic N and P concentration, initial soluble N and P concentrations, saturated conductivity, and lateral hydraulic conductivity.
Weather	Eischeid et al. (2000), Daly et al. (1997, 2002), and Di Luzio et al. (2008)	1960-2006	Daily precipitation and maximum and minimum temperature.
8-digit watershed channel length and slope	HUMUS/SWAT database	--	8-digit watershed channel length and slope for each 8-digit watershed in the U.S., used for estimating the times of concentration in APEX for the purpose of calculating the sediment delivery ratio from the APEX simulation site to the 8-digit outlet.

[a] 2001 National Land Cover Data were used to update the hydrological response units (HRUs) in the HUMUS/SWAT system. The HRUs of uncultivated land uses were simulated using SWAT, but the cultivated cropland was simulated using APEX.

[b] CEAP = Conservation Effects Assessment Project, CREP = Conservation Reserve Enhancement Program, NCSS = National Cooperative Soil Survey, NASIS = National Soil Information System, NRI = National Resources Inventory, NRCS = Natural Resources Conservation Service, and NSSL = National Soil Survey Laboratory.

Table 2. Structural conservation practices simulated in CEAP cropland national assessment.

Structural Conservation Practices	Simulated by Modifying APEX Parameters[a]		Field Configuration
Managed infield flow interceptor	P factor[b]	LUN	Within field (one subarea)
Contour farming	0.6-0.9	+2	
Strip cropping	0.5-0.9	+4	
Contour buffer strips	0.25-0.45	+4	
Engineered flow interceptors	P factor[b]	LUN	Within field (one subarea)
Terraces	0.45-0.75	+2	
Grass terraces	0.25-0.45	+4	
Vegetative barrier	0.45-0.75	+2	
Diversions	SPLG = 0.5 × NRI		
Riparian buffers			Two or three subareas: upland subarea, grass filter strip, and forest buffer (fig. 3).
Filter strips	Simulated as a grass filter	LUN = 26	
Riparian herbaceous or forest buffers	Simulated as a grass filter and a forest buffer	LUN = 26 and 29	
	P factor = 0.6, RCHC = 0.001, and RCHN = 0.2	Grass filter: FFPQ = 0.95, RCHS = 0.25 × NRI; Forest buffer: FFPQ = 0.85, RCHS = 0.1 × NRI	
Wind erosion control	Unsheltered field size[c]	Unsheltered distance with strip cropping	Within field (one subarea)
Hedgerows	0.06 km × 0.06 km	0.03 km	
Cross-wind practices	0.04 km × 0.04 km	0.03 km	
Windbreak/shelterbelt	0.03 km × 0.03 km	0.02 km	
Herbaceous wind barrier	0.04 km × 0.04 km	0.03 km	
Field borders	P factor = 0.95		Within field (one subarea)
Grade stabilization structures	RCHS = 0.1 × NRI		Two subareas: upland subarea, and downstream subarea with a routing channel.
Grass waterway	RCHC = 0.01 (prior = 1), RCHN = 0.08 (prior = 0.04), and RCHS = 0.52 × NRI	Routing reach = 0.01 m depth, 0.1 m bottom width, 3.0 m top width (prior = 0.75 m × 0.75 m × 0.75 m); RFPW = 20 m	Two subareas: upland subarea, and downstream subarea with a routing channel.

[a] Parameter changes for combinations between different groups or within group are not listed here, see Potter et al. (2009) for more detail. FFPQ = fraction floodplain flow (e.g., FFPQ = 0.95 means that 95% is overland flow in the floodplain and 5% channel flow), NRI = National Resources Inventory reported value, LUN = land use number for looking up curve number, RCHC = channel USLE *C* factor of routing reach, RCHN = channel Manning's "n" of routing reach, RCHS = channel slope of routing reach (m m-1), RFPW = floodplain width (m), and SPLG = average upland slope length (m).
[b] Vary with overland slope.
[c] Length × width; without practices, the field was assumed to be 0.4 km × 0.4 km.

data elements in order to complete the data record for these created points. Initial weights for created points and for observed points were adjusted during the estimation process using ratio adjustments and small area estimation. Control totals for surface area, federal land, and large water areas, derived from GIS databases, were maintained throughout the process. Finally, the weights were adjusted using iterative proportional scaling (raking) so that the new database produced acreage estimates for broad land cover/use categories for historical years that closely matched the previously published estimates. Estimation weights for the NRI-CEAP cultivated cropland sample points in the UMRB were developed in a manner consistent with development of weights for the annual NRI (Goebel, 2009). Therefore, the NRI-CEAP samples are statistically representative of cultivated cropland and formerly cultivated land currently in long-term conserving cover and capture the diversity of soils, climate, field characteristics, farming practices, and conservation systems throughout the agricultural land in the U.S.

The NRI-CEAP points served as "representative fields" to be simulated using APEX. A total of 5534 representative cultivated fields (3703 NRI-CEAP cropland points and 1831 CRP points) were included in the APEX run for the UMRB. The statistical acreage weights associated with each representative field ranged from 2400 to 554,000 ha. APEX outputs two sets of results: (1) the edge-of-field outputs, and (2) the 8-digit watershed output to SWAT by using delivery ratios computed within APEX considering the 8-digit watershed channel lengths and slopes (described in the Delivery Ratios section).

The statistical sample weight associated with each sample point was used to aggregate the edge-of-field APEX modeling results for national reporting of onsite benefits. The watershed outputs (delivery ratios applied within APEX, see Delivery Ratios section) to SWAT from each APEX simulation unit (one or multiple subareas depending on conservation practices in use) were area weighted and added for each 8-digit watershed as follows:

$$SWAT_{in} = \frac{\sum_{i=1}^{n}\left(APEX_{toSWAT\_i} \cdot AWeight_i\right)}{\sum_{i=1}^{n} AWeight_i} \qquad (1)$$

where $SWAT_{in}$ is the aggregated APEX watershed output to SWAT for one 8-digit watershed (e.g., water yield in mm or sediment yield in Mg ha^{-1}), $APEX_{toSWAT\_i}$ is the corresponding APEX watershed output to SWAT for one APEX simulation unit *i* in the 8-digit watershed, $AWeight_i$ is the acreage weight of point *i* (in ha), and *n* is the total number of NRI-CEAP units simulated for this 8-digit watershed.

In concept, this process is similar to handling SWAT HRUs, where individual HRUs are simulated independently, area weighted, and added for each subbasin. The results were integrated into HUMUS/SWAT at the 8-digit watershed level with SWAT's simulation of uncultivated land. Next, the SWAT model channel and routing procedures take place for further routing downstream in order to estimate the offsite effects at each major river basin outlet. HUMUS/SWAT accounts for the transport of water, sediment, pesticides, and nutrients from the land to receiving streams and routes the flow downstream to the next watershed.

Assessment of Conservation Practices

The modeling approach was used for scenario analysis for evaluating conservation treatments. Only a brief description is provided here since it is not the focus of this article. More details can be found in USDA-NRCS (2010). The APEX-HUMUS/SWAT simulations provide comparisons between the baseline conservation condition and the no-practice scenario, which were used to assess the effects of current conservation practices. The adequacy of the conservation practices in use in the UMRB was evaluated to identify remaining conservation treatment needs for controlling sediment and nutrient losses. Field-level results for the baseline conservation conditions and acceptable levels for field-level losses were used in the CEAP cropland study to evaluate the adequacy of conservation treatment. Two types of areas needing treatment were identified: (1) under-treated acres, and (2) critical under-treated acres, which is a subset of under-treated acres. Adequate conservation treatment consists of combinations of conservation practices that control sediment loss due to water erosion, nitrogen lost with surface runoff, and phosphorus lost with surface runoff. Four alternative conservation treatment scenarios were simulated to evaluate the potential gains from further conservation treatment in the UMRB: (1) treatment of critical under-treated acres with water erosion control practices, (2) treatment of all under-treated acres with water erosion control practices, (3) treatment of critical under-treated acres with nutrient management practices in addition to water erosion control practices to reduce nutrient losses, and (4) treatment of all under-treated acres with nutrient management practices in addition to water erosion control practices to address nutrient losses. For each scenario, only the conditions for cultivated cropland were changed; all other aspects of the simulations remained the same, including sediment and nutrient loads from point sources and uncultivated land uses.

Modeling Conservation Practices

APEX requires weather, soil, site, and field management information. The available data and sources for APEX modeling are summarized in table 1. In this study, conservation practices are classified into cultural practices and structural practices. Cultural practices are those that a farmer or land manager implements, usually based on annual decisions, by changing the way cropland is managed to achieve production or conservation goals. Reducing tillage intensity through practices such as conservation tillage, improving vegetative cover over the soil surface by using cover crops, conservation crop rotations, and applying mulch are examples of cultural practices. Managing nutrient applications through a nutrient management plan and controlling pests using integrated pest management are other cultural techniques. APEX management capabilities include processes built for simulating these practices as physically and realistically as possible. For example, tillage simulation is designed to simulate mixing nutrients and crop residues, changing surface roughness and bulk density, and subsequent settling. Crop growth processes simulate the growth of plants and vary among vegetables, field crops (cover crops, crop rotations), annual and perennial grasses, brush, trees, and mixed stands. During the plant growth cycle, the crop management factor (USLE *C* factor) is updated daily to reflect change in plant cover.

Structural practices are considered permanent practices that require more than annual management decisions. These practices are considered permanent because implementation usually requires engineering design, surveying, and contracting with a vendor. Planting of perennial grasses, trees, or herbaceous cover to achieve a desired conservation effect are also considered structural practices. Practices such as contour farming and strip cropping tend to "support" cultural management practices. Structural practices such as terraces and diversions work by intercepting and diverting surface runoff to stable outlets. Other structural practices, including field borders, buffer strips, and riparian buffers, filter surface runoff and allow contaminated water to infiltrate into the soil. To capture combined effects and eliminate duplicate functions, practices were assigned into one of the following functional categories: managed in-field flow interceptor, engineered in-field flow interceptor, riparian buffer, and wind erosion control (table 2). APEX provides considerable flexibility for simulating conservation practice effects. The model allows users to simulate effects using empirically based techniques, theoretical techniques, or a combination of both.

In this study, managed and engineered flow interceptor effects were simulated by changes in the conservation practice factor (P factor), slope, slope length, or curve number. Riparian areas were simulated as areas of grasses or trees separate from the cropland area which the water runoff from the cropland had to cross prior to reaching the "edge of field." Effects from wind erosion control were simulated by changing the unsheltered distance in the field length and width. Field border effects were simulated by reducing the P factor by 5%. Grade stabilization structures and grass waterways were simulated by channelizing water flow through part of the cropped field. Where a grade stabilization structure is reported, a steep-gradient ditch or channel with high-velocity flow is the assumed prior condition. The grade stabilization structure is represented by reducing the channel gradient and increasing its surface roughness. For a grass waterway, the prior condition includes an erodible earth ditch or channel with dimensions of 0.75 m depth and 0.75 m for both bottom and top width. Practice effects are simulated by changing the channel cover factor, surface roughness, and dimensions. In addition, the flood plain width was set to 20 m so that the runoff water would flow in the floodplain (table 2).

Curve Number

Daily runoff volume is calculated using a modification of the NRCS curve number method (Mockus, 1969; USDA-NRCS, 2004b). In the curve number method of runoff estimation, the combination of a hydrologic soil group and a land cover class indicates the potential for surface runoff.

Table 3. Land use number and curve number setting (USDA-NRCS, 2004a; Williams et al., 1990).

Land Use Type	Conservation Practice	Hydrologic Condition	Land Use Number (LUN)	Curve Number (by Soil Hydrologic Group)			
				A	B	C	D
Fallow	All	All	1	77	86	91	94
Row crops	None	Poor	2	72	81	88	91
		Good	3	67	78	85	89
	Contour, strip cropping, or terrace	Poor	4	70	79	84	88
		Good	5	65	75	82	86
	Two or more of contour, strip, and terrace	Poor	6	66	74	80	82
		Good	7	62	71	78	81
Small grain	None	Poor	8	65	76	84	88
		Good	9	63	75	83	87
	Contour, strip, or terrace	Poor	10	63	74	82	85
		Good	11	61	73	81	84
	Two or more of contour, strip, and terrace	Poor	12	61	72	79	82
		Good	13	59	70	78	81
Close-seeded legume	None	Poor	14	66	77	85	89
		Good	15	58	72	81	85
	Contour, strip, or terrace	Poor	16	64	75	83	85
		Good	17	55	69	78	83
	Two or more of contour, strip, and terrace	Poor	18	63	73	80	83
		Good	19	51	67	76	80
Pasture or range	None	Poor	20	68	79	86	89
		Fair	21	49	69	79	84
		Good	22	39	61	74	80
	Two or more of contour, strip, and terrace	Poor	23	47	67	81	88
		Fair	24	25	59	75	83
		Good	25	6	35	70	79
Meadow	Continuous grass, protected from grazing and generally mowed for hay	--	26	30	58	71	78
Woods	None	Poor	27	45	66	77	83
		Fair	28	36	60	73	79
		Good	29	25	55	70	77

Changes in land use, conservation practices, or hydrologic conditions change the quantity of surface water runoff, thus affecting the transport of waterborne soil, soil-bound nutrients, and soluble nutrients. This effect is simulated in APEX by changing the curve number. The APEX model can use land use number (LUN) to designate a curve number. The LUN classifies an area by land use type (i.e., row crops, small grains, fallow, pasture, grass, trees, road), soil hydrologic group, conservation practice (i.e., none, contour farming, strip cropping, terraces), and cropland management decisions on surface hydrology (poor or good hydrologic condition) (USDA-NRCS, 2004a). A lower curve number value, which leads to greater runoff, within the same soil hydrologic group has a higher LUN, with only a few exceptions (table 3). Therefore, we carefully checked each LUN while modifying the LUNs from a no-practice condition to the conditions with conservation practices, such as contour farming, strip cropping, contour buffer strips, terraces, vegetative barrier, and filter strips (table 2), so that the conditions with these conservation practices will have less runoff potential than the no-practice conditions.

Conservation Practice Effects (P Factor)

Conservation practices including contours, strip cropping, contour buffer strips, and terraces can be simulated by adjusting the RUSLE conservation support practice factor (P factor), slope length, and curve number. The P factor is an empirically derived factor that is multiplied into the RUSLE-derived erosion estimate to account for effects from conservation support practices. The P factor varies from 1.0 (to simulate straight-row, up-and-downhill farming) to 0.15 (e.g., combination of contour buffer strips and grass terraces) to represent multiple practices on a gentle slope based on literature values. The P factor values (table 2) were set up based on literature values (e.g., Wischmeier and Smith, 1978). Bracmort et al. (2006) simulated the effects of parallel terraces by modifying the P factor (0.2 to 0.3), slope length, and curve number. Yin et al. (2009) simulated the effects of mixed wood and grass with horizontal terraces or woodland with ditches by adjusting the P factor (0.21 to 0.29) and the curve number. Secchi et al. (2007) used the P factor to represent contouring and terraces. Tuppad et al. (2010) also represented terraces and contour farming by conservation support practice P factor (0.1 to 0.5) and curve number.

Channel Flow Technique

Channel flow techniques are employed for conservation practices designed to create a stable channel where the prior condition is an unstable or degrading channel or gully. The basic concept is to parameterize the model so that very little channel degradation occurs when practices are in place. Easily eroded channel material and high velocity water flow through the channel are assumed to be the two main drivers of channel degradation. Practice techniques target the two drivers. Unstable narrow channels consisting of easily eroded earth in pre-BMP condition are converted into stable channels by changing the channel dimensions (depth, top width, and bottom width), Manning's roughness coefficient, and the channel *C* factor (Bracmort et al., 2006; Secchi et al., 2007). Flow in steep, high-velocity channels in pre-BMP conditions can be slowed by reducing the channel gradient (table 2). For this scale study with limited resources, the relative uncertainty of these predictions is high due to the lack of data necessary to define the prior and current channel dimensions and channel erodibility for each simulation site.

Riparian Simulation Technique

Riparian simulation techniques entail spreading and slowing water flow from an upland cropped area across buffer strips consisting of grasses, shrubs, and/or trees. Simulating riparian buffers make use of the model feature that allows areas to be subdivided into fields, soil types, or landscape positions. Flow is spread across the buffer strip using a special flood flow subroutine that is triggered by setting a filter flag, designating the fraction of flow spreading across the filter, and setting the floodplain dimensions. Figure 3 illustrates the field configuration and various subareas associated with a riparian buffer system.

Wind Erosion Estimates and Unsheltered Distance

Wind erosion is estimated in APEX using the Wind Erosion Continuous Simulation (WECS) model. WECS incorporates the daily distribution of wind speeds as the force driving wind erosion (Williams, 1995). The wind erosion estimated in APEX represents the amount of eroded material leaving the field. In wind erosion science, a field is defined as the unsheltered distance along the prevailing wind erosion direction for the field or area being evaluated. WECS does not account for any material deposited in fence rows, barrow ditches, or other barriers on the downwind side of the field. Estimated wind erosion can be adjusted based on soil properties, surface roughness, cover, and unsheltered distance across the field in the wind direction. For structural conservation practices, only the unsheltered distance factors (field length and field width) are adjusted when accounting for the wind erosion control practices (table 2).

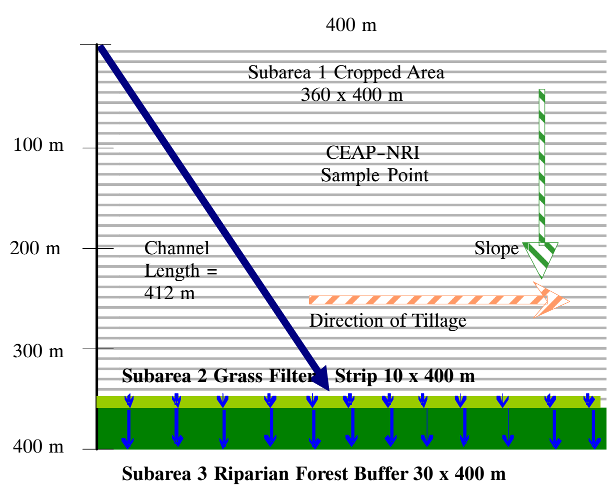


Figure 3. Field configuration used to represent a riparian buffer (shown with tillage across the slope).

Delivery Ratios

For the CEAP cropland national assessment, the fundamental modeling units are the NRI-CEAP points (cultivated lands) and CRP points representing cultivated land uses in the HUMUS system, and the remaining HRUs representing uncultivated land uses within each 8-digit watershed. The amount of sediment delivered to the 8-digit watershed outlet from each simulation unit was calculated using the sediment delivery ratio (SDR) estimated in APEX (for cultivated lands) and SWAT (for uncultivated lands) as follows:

$$Y_{B\_i} = Y_{S\_i} \cdot SDR_i \tag{2}$$

where Y_{B_i} is the sediment yield at the 8-digit watershed outlet for simulation unit *i*, Y_{S_i} is the sediment yield at the edge-of-field of simulation unit *i*, and SDR_i is the *SDR* for the simulation unit *i*.

The APEX and SWAT models simulate the sediment yield using the following equations developed based on the Universal Soil Loss Equation (USLE) and Modified USLE (Williams and Izaurralde, 2006; Neitsch et al., 2005):

$$Y_{S\_i} = X \cdot K \cdot C \cdot P \cdot LS \cdot CFRG \tag{3}$$

$$X = 2.5 \cdot \left(Q_{surf} \cdot q_{peak}\right)^{0.5} \text{ (for APEX)} \tag{4}$$

$$X = 11.8 \cdot \left(Q_{surf} \cdot q_{peak} \cdot area_{hru}\right)^{0.56} \text{ (for SWAT)} \tag{5}$$

where *X* is the runoff factor, *K* is the USLE soil erodibility factor, *C* is the USLE cover and management factor, *P* is the USLE support practice factor, *LS* is the USLE topographic factor, *CFRG* is the coarse fragment factor, Q_{surf} is the surface runoff volume (mm), q_{peak} is the peak runoff rate (mm h^{-1} in APEX and m^3 s^{-1} in SWAT), and $area_{hru}$ is the area of the HRU (ha).

In both APEX and SWAT, Q_{surf} is estimated using a modification of the NRCS curve number method (Mockus, 1969; USDA-NRCS, 2004b), and q_{peak} is estimated using the modified rational formula (Williams, 1995):

$$Q_{surf} = \frac{(P - 0.2S)^2}{(P + 0.8S)} \tag{6}$$

$$S = S_{prev} + PET \cdot \exp\left(-CNIC \cdot \frac{S_{prev}}{S_{\max}}\right) - P_{prev} + Q_{prev} \tag{7}$$

$$q_{peak} = \frac{C \cdot i \cdot Area}{3.6} \tag{8}$$

where *P* is rainfall depth for the day (mm), *S* is the retention parameter for a given day (mm), S_{prev} is the retention parameter on the previous day (mm), *PET* is the potential evapotranspiration for the day (mm d^{-1}), *CNIC* is the weighting coefficient used to calculate the retention coefficient for daily curve number calculations dependent on plant evapotranspiration, S_{max} is the maximum value the retention parameter can achieve on any given day (mm), P_{prev} is rainfall depth on the previous day (mm), Q_{prev} is surface runoff depth on the previous (mm), C is a runoff coefficient, i is the rainfall intensity (mm h^{-1}), *Area* is the subbasin area (km^2), and 3.6 is a unit conversion factor.

There are typically 20+ NRI-CEAP points simulated with APEX in each 8-digit watershed in the UMRB. These sample points provide statistical samples representing the diversity of soils and other conditions on the landscape. There are about 12 to 20 HRUs representing the uncultivated land uses within each 8-digit watershed that are simulated with SWAT. Each HRU represents a unique land use and soil combination, which is a portion of the 8-digit watershed area and does not represent a contiguous land area; therefore, they are distributed throughout the 8-digit watershed. Faced with this limitation, the development of the SDR in this study depends on the efficiency of the algorithm with modest input parameter requirements. The SDR for each simulation unit is estimated (within both APEX and SWAT) as a function of the ratio of time of concentration of the simulation unit to time of concentration of the 8-digit watershed (developed by Jimmy R. Williams and Jeffrey G. Arnold for CEAP in 2008):

$$SDR_i = \left(\frac{t_{cS}}{t_{cB}}\right)^{dr\_\exp} \tag{9}$$

where SDR_i is the SDR for each site or HRU, t_{cS} is the time of concentration of the simulation site (h), t_{cB} is the time of concentration of the 8-digit watershed (h), and *dr_exp* is the delivery ratio exponent in transforming APEX and SWAT small-area simulated sediment yield to 8-digit basin sediment yield. In this study, *dr_exp* was adjusted based on available sediment yield data within the UMRB region. Time of concentration is related to watershed characteristics such as slope, slope length, landscape characteristics, and drainage area.

In APEX, the times of concentration for the development of SDR are estimated with the Kirpich equation (Kirpich, 1940) in metric form:

$$t_c = 0.0663 \cdot \frac{L^{0.77}}{S^{0.385}} \tag{10}$$

where L is the watershed length along the main stem (km), and S is the main stem slope (m m^{-1}). Substituting t_{cS} and t_{cB} calculated from equation 10 into equation 9 yields:

$$SDR_i = \left(\left(\frac{L_S}{L_B}\right)^{0.77} \cdot \left(\frac{S_B}{S_S}\right)^{0.385}\right)^{dr\_\exp} \tag{11}$$

where L_B and S_B are the 8-digit watershed channel length (km) and channel slope (m m^{-1}), respectively; L_S and S_S are the APEX simulation site length (km) and slope (m m^{-1}), respectively, which are estimated based on drainage area, NRI data, and structural conservation practices (Potter et al., 2009).

In SWAT, the time of concentration is calculated by summing the overland flow time (the time required for flow from the most remote point in the subbasin to reach the channel) and the channel flow time (the time required for flow in the upstream channels to reach the outlet). Total time of concentration is the sum of overland and channel flow times:

$$t_{c,hru} = t_{ov} + t_{ch,hru} \tag{12}$$

$$t_{c,sub} = t_{ov} + t_{ch,sub} \tag{13}$$

where $t_{c,hru}$ is the total time of concentration for the HRU (h), t_{ov} is the time of concentration for overland flow (h), $t_{ch,hru}$ is the time of concentration for HRU channel flow (h), $t_{c,sub}$ is the total time of concentration for the subbasin (h), and $t_{ch,sub}$ is the time of concentration for the subbasin channel flow (h).

Tributary channel characteristics related to the HRU are used in computing overland flow time of concentration:

$$t_{ov} = \frac{L_{slp}^{\;0.6} \cdot n^{0.6}}{18 \cdot slp^{0.3}} \tag{14}$$

where L_{slp} is the average subbasin slope length (m), *slp* is the average HRU slope in the subbasin (m m^{-1}), and n is Manning's roughness coefficient for the overland flow, representing characteristics of the land surface with residue cover or tillage operations. Manning's "n" ranges from 0.01 to 0.60.

The times of concentration for channel flow are computed as:

$$t_{ch,hru} = \frac{0.62 \cdot L \cdot hru\_prop \cdot n^{0.75}}{hru\_area^{0.125} \cdot slp_{ch}^{\;0.375}} \tag{15}$$

$$t_{ch,sub} = \frac{0.62 \cdot L \cdot n^{0.75}}{Sub\_area^{0.125} \cdot slp_{ch}^{\;0.375}} \tag{16}$$

where L is the channel length from the most distant point to the subbasin outlet or the longest tributary channel length (km), *hru_prop* is the proportion of the tributary channel length in the HRU, n is Manning's roughness coefficient for the channel representing the characteristics of the channel (ranges from 0.025 through 0.100), *hru_area* is the area of the HRU, slp_{ch} is the average slope of the longest tributary channel (m m^{-1}), and *Sub_area* is the subbasin area (km^2). The value of *hru_prop* is estimated by multiplying the longest tributary channel length by the ratio of HRU area to subbasin area.

Calibration and Validation of Water and Sediment Yields

Water Yield

For regional- or large-scale modeling studies, flow calibration and validation are often limited to one or two gauging stations on the river near or at the watershed outlet without adequate spatial validation due to the availability of observed flow data (Hao et al., 2004; Jha et al., 2006). In this study, although at the 8-digit watershed level APEX was run for cultivated cropland and SWAT was run for uncultivated land separately, the models were coupled to make the overall water yield acceptable at all 8-digit watersheds level. Flow was also validated at multiple gauging stations along the major river at Jordan, Minnesota; Clinton, Iowa; Wapello, Iowa; Valley City, Illinois; and Alton/Grafton, Illinois (fig. 1).

The target spatial water yield at the 8-digit watershed level (fig. 2b) for model calibration was obtained based on average runoff contours due to lack of other similar datasets that capture the spatial variation of runoff over regions. Several studies have used the average runoff contours for regional-scale studies (e.g., Wolock and McCabe, 1999; Kannan et al., 2008a; Santhi et al., 2008). Gebert et al. (1987) produced an average annual runoff contour map for the conterminous U.S. using measured streamflow from 5,951 USGS gauging stations during the period 1951 to 1980. An interpolated runoff map (cell size 41.5 km × 41.5 km) was developed based on the runoff contours of Gebert et al. (1987) in order to obtain an average runoff value (30 years) for each 8-digit watershed (fig. 2b). The mean annual runoff estimates of 8-digit watersheds estimated from runoff contours have some limitations. For example, within the conterminous U.S., some 8-digit watersheds are hydrologically closed, meaning no runoff leaves the unit. However, the runoff contour based estimates will produce some runoff. If we try to match the predicted runoff to these values, it may not be correct. Another uncertainty might be for places where the contour estimates were computed based on a limited number of stream gauges. The uncertainty of runoff estimates from runoff contours was also discussed by Rochelle et al. (1989).

Both SWAT and APEX were calibrated to capture the spatial variation in long-term average annual runoff by adjusting flow-influential model input parameters (table 4). Calibration was performed for water yield at the 8-digit watershed level to ensure local water balance. The flow calibration procedure was designed to calibrate one parameter at a time. Not all the parameters were calibrated for each 8-digit watershed. Some 8-digit watersheds were calibrated by adjusting two or three parameters alone. In some 8-digit watersheds, all the parameters were adjusted to get a better match between predictions and observations. Therefore, the number of parameters adjusted depends on where the mismatch occurred (i.e., surface runoff, base flow, or water yield) and the extent of the mismatch. The soil water depletion coefficient was used to calculate the retention coefficient in the curve number method for daily curve number calculations based on plant evapotranspiration (Kannan et al., 2008b; Wang et al., 2009). The Hargreaves PET equation exponent and coefficient were used to adjust evapotranspiration (ET) estimated by the Hargreaves method (Hargreaves and Samani, 1985) and water yield. Curve number was used to adjust surface runoff. The minimum threshold depth of water in the shallow aquifer required for groundwater flow to occur, groundwater re-evaporation coefficient, soil-available water holding capacity, and plant and soil evaporation compensation factors in SWAT were used to adjust subsurface flow and the total water yield (table 4). The return flow ratio is the ratio of return flow to channel and the total percolation flow. The tile drainage saturated hydraulic conductivity coefficient was used to control the upper limit of tile drain flow. The adjustable ranges of these parameters (table 4) were based on model documentation (Williams et al., 2004; Neitsch et al., 2002) and reported ranges (Santhi et al., 2001; Wang et al., 2006).

The APEX and HUMUS/SWAT system was run with weather data from 1960 through 2006 (47 years) to represent long-term weather conditions in the UMRB. The modeling system was calibrated with 30 years of data (1961-1990) and validated with 16 years of data (1991-2006). Average annual runoff from each 8-digit watershed was used for spatial calibration. Monthly and annual average streamflow at selected gauging stations along the Mississippi River were used for temporal calibration and validation. Calibration of average annual runoff helps ensure local water balance at the 8-digit watershed level. The temporal calibration and validation (monthly and annual) was performed to ensure seasonal and annual variability.

Statistical measures such as mean, standard deviation (SD), coefficient of determination (R^2), and Nash-Sutcliffe efficiency (NSE; Nash and Sutcliffe, 1970) were used to evaluate the annual and monthly simulated flows against the measured flows at the gauges. If the R^2 values are greater than 0.6 and NSE values are greater than 0.5, then the model predictions are considered "acceptable" (Santhi et al., 2001; Moriasi et al., 2007).

Sediment Yield

Continuous sediment data from the gauging stations within the UMRB were not available. Grab samples of monitored data of suspended sediment were available from USGS for selected gauging stations in the UMRB. Typically, there were 10 to 20 samples per year available for a few years. These grab sample concentrations, along with observed daily flow, were processed in a load estimator program (Runkel et al., 2004) to determine the annual average loads of suspended sediment. The regular split-sample procedure for calibration and validation was not performed because of limited availability of data. Instead, the entire set of available sediment data at Valley City, Illinois, was used to calibrate the modeling system, and the entire set of sediment data at Alton/Grafton, Illinois, was used for validation.

Table 4. Calibration parameters in SWAT and APEX, their range and their effect on different components of runoff.

	Changes			Range Used	
Parameter	Surface Runoff	Subsurface Runoff	Water Yield	Minimum	Maximum
Soil water depletion coefficient (APEX and SWAT)	x	x	x	0.5	1.50
Hargreaves PET equation exponent (APEX)	x	x	x	0.5	0.6
Hargreaves PET coefficient (SWAT)	x	x	x	0.0019	0.0027
Curve number	x	x	x	-5	+5
Min. water depth in shallow aquifer for groundwater (SWAT)	x	x	x	-3	+3
Groundwater re-evaporation coefficient (SWAT)	--	x	x	0.02	0.2
Soil available water holding capacity (SWAT)	--	x	x	-0.04	+0.04
Plant evaporation compensation factor (SWAT)	--	x	x	0.01	0.99
Soil evaporation compensation factor (SWAT)	--	--	x	0.73	0.99
Return flow ratio (APEX)	--	--	x	0.05	0.95
Tile drainage saturated hydraulic conductivity coeff. (APEX)	Tile drain flow		x	0.8	3.0

The delivery ratio exponent (*dr_exp* in eq. 9), which accounts for losses occurring from the fields to the 8-digit watershed outlet, was adjusted. A value of 0.2 was used in APEX and 0.5 in SWAT for the UMRB, so the sediment budget and losses from cultivated lands and from uncultivated lands are realistic. In HUMUS-SWAT setup, channel bed and bank erosion for each reach is accounted for by parameters such as channel erodibility, channel cover factor, and channel slope. The channel slopes and dimensions were estimated from a digit elevation model (DEM) and regression relationship developed for channel depth and width. A quality inspection of channel slopes and dimensions was conducted, and necessary updates were made based on available information, e.g., the width and depth of the Mississippi River at certain locations. The instream sediment-related parameters in SWAT were adjusted for the channel and flood plain deposition and degradation to be realistic. SWAT uses the modified Bagnold stream power equation for channel sediment routing. Using this equation, the maximum amount of sediment that can be transported by water from a reach segment is related to the peak channel velocity estimated for each 8-digit channel reach using a linear parameter (*spcon*) and exponential parameter (*spexp*), as shown below (Arnold et al., 1995; Neitsch et al., 2002):

$$conc_{sed,ch,mx} = spcon \cdot v_{ch,pk}^{\;spexp} \tag{17}$$

where $conc_{sed,ch,mx}$ is the maximum concentration of sediment that can be transported by the water (ton m^{-3} or kg L^{-1}), *spcon* is a user-defined coefficient and varies between 0.0001 and 0.03, $v_{ch,pk}$ is the peak channel velocity (m s^{-1}), and *spexp* is an exponent and can vary between 1.0 and 2.0. In the original Bagnold stream power equation, *spexp* was set at 1.5 (Arnold et al., 1995; Neitsch et al., 2005). For the CEAP national assessment, the sediment routing process was modified by multiplying *spcon* with an exponential coefficient of the cumulative drainage area of the river reach (drainage area at the point of 8-digit watershed outlet along the river in km^2) to allow main channel losses to be realistic in large river basins. For the UMRB, the exponential coefficient was set to 0.5, *spcon* was set to 0.03, and *spexp* was set to 1.0.

Results and Discussion

Water Yield

The average annual predicted and targeted water yields for the 131 eight-digit watersheds in the UMRB are shown in figure 4. Predicted and observed water yield patterns are in concurrence with the precipitation patterns of this basin. The predicted long-term average annual water yield over the 131 eight-digit watersheds is 225.4 mm (66.8 mm SD), which compare closely with the observed mean of 203.1 mm (66.4 mm SD). The predicted average annual water yields for all the 8-digit watersheds are within ±30% of the observed values (fig. 5a). The 25% to 30% error in average annual water yield for the western section of the watershed is due to underestimation of subsurface flow. The underestimation of subsurface flow is due to overestimation of ET in the forest and forested wetlands of those 8-digit watersheds. The calibration parameters were not adequate to address this, resulting in a greater difference between predicted and target values. The R^2 value is 0.86, and the NSE value is 0.74. With recognized uncertainty in the targeted data (Rochelle et al., 1989), model results within 10% to 31% of observed values are within the average uncertainty range (Harmel et al., 2006). The modeling results at the 8-digit watershed level are considered reasonable. Further comparisons at five stream gauges along the major rivers, located in the Minnesota River (Jordan, Minn.), Iowa River (Wapello, Iowa), Illinois River (Valley City, Ill.), and Mississippi River (Clinton, Iowa, and Alton/Grafton, Ill.) (fig. 1), were conducted based on annual and monthly predicted and observed values for the calibration period (1961-1990) (table 5).

Means and standard deviations of both annual and monthly predicted and observed water yields are in close agreement (tables 5 and 6), indicating the similarity in observed and predicted water yield probability distribution. The R^2 values ranged from 0.66 to 0.94, and the NSE values ranged from 0.59 to 0.87, with PBIAS values within ±20% and RSR values from 0.30 to 0.64 for all the gauges during the calibration period (table 5). During the validation period (1991-2006), the R^2 values ranged from 0.68 to 0.98, and the NSE values ranged from 0.50 to 0.87, with RSR values from 0.36 to 0.69 for all the gauges (table 6). The model performance evaluation measures suggest an overall satisfactory agreement between observed and simulated flows at both annual and monthly time steps (1961-2006) throughout the river basin.

The long-term average annual observed streamflow varied from 114 mm at the Jordan, Minnesota, station to 307 mm at the Valley City, Illinois, station. Predicted flow matched this spatial variation. The APEX and HUMUS/SWAT system captured the temporal variation reasonably well (figs. 6, 7, and 8). Predicted annual flow results captured the patterns of observed values during both the calibration

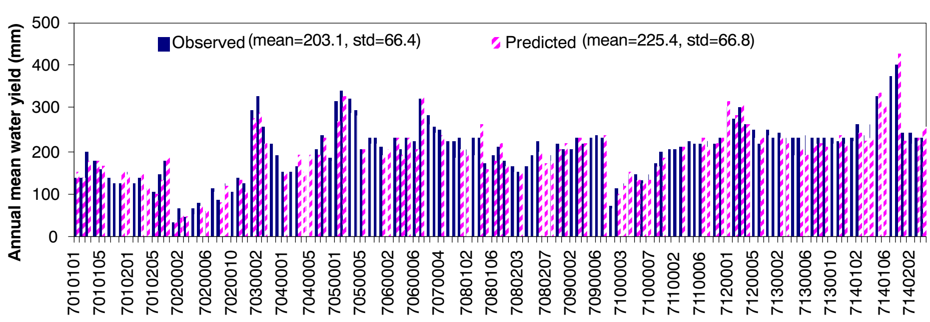
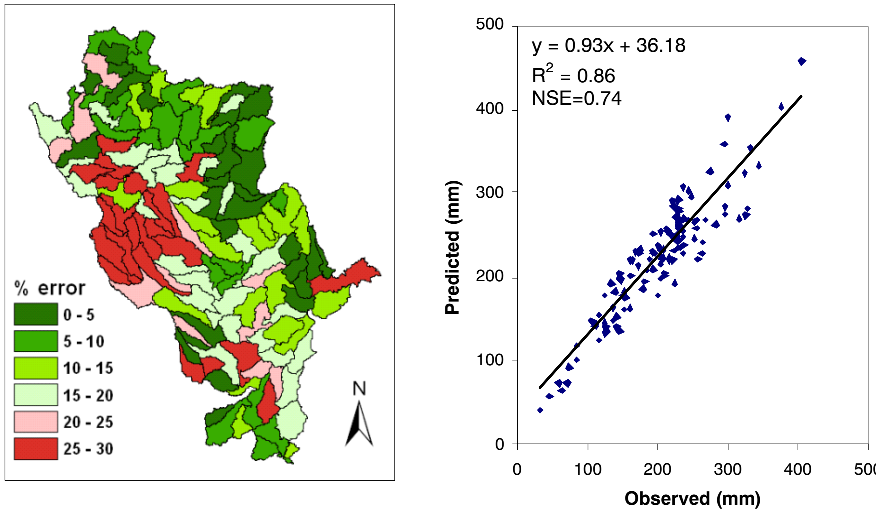


Figure 4. Predicted vs. observed annual average water yield for 8-digit watersheds in the upper Mississippi River basin.



(a) Percentage difference

(b) Regression of predicted vs. observed water yield

Figure 5. (a) Percentage difference between predictions and observations of annual average water yield and (b) regression between observed and predicted values at 8-digit watersheds in the upper Mississippi River basin.

Table 5. Model performance evaluation of water yield (mm) for the calibration period (1961-1990) in the upper Mississippi River basin.

		Gauging Station				
	Statistic[a]	Jordan, Minn.	Clinton, Iowa	Wapello, Iowa	Valley City, Ill.	Alton/Grafton, Ill.
River		Minnesota River	Mississippi River	Iowa River	Illinois River	Mississippi River
Drainage area (km^2)		41,958	221,704	32,375	69,264	444,183
Annual	Observed	92.5 (55.3)	194.0 (54.0)	233.3 (108.7)	302.8 (97.9)	224.4 (74.4)
	Predicted	98.9 (45.4)	193.2 (52.9)	215.8 (88.0)	358.7 (104.8)	218.4 (65.2)
	R^2	0.84	0.83	0.92	0.94	0.94
	NSE	0.81	0.83	0.87	0.59	0.92
	PBIAS (%)	6.9	-0.4	-7.5	18.4	-2.7
	RSR	0.44	0.41	0.35	0.63	0.30
Monthly	Observed	7.9 (10.5)	16.2 (9.9)	19.5 (16.6)	25.3 (18.7)	18.7 (11.9)
	Predicted	8.0 (9.7)	16.1 (8.9)	18.0 (17.6)	29.9 (19.1)	18.2 (10.6)
	R^2	0.67	0.70	0.66	0.88	0.84
	NSE	0.66	0.70	0.59	0.81	0.84
	PBIAS (%)	1.6	-0.4	-7.5	18.4	-2.7
	RSR	0.59	0.55	0.64	0.43	0.40

[a] Observed and predicted values are means (standard deviations in parentheses. RSR = ratio of the root mean square error to the standard deviation of observed data.

Table 6. Model performance evaluation of water yield (mm) for the validation period (1991-2006) in the upper Mississippi River basin.

		Gauging Station				
	Statistic[a]	Jordan, Minn.	Clinton, Iowa	Wapello, Iowa	Valley City, Ill.	Alton/Grafton, Ill.
Annual	Observed	150.7 (70.2)	234.2 (46.7)	287.9 (163.9)	314.0 (109.6)	250.0 (81.1)
	Predicted	111.0 (51.4)	222.1 (38.9)	227.8 (115.5)	356.9 (117.8)	235.0 (53.0)
	R^2	0.88	0.76	0.96	0.98	0.93
	NSE	0.50	0.68	0.76	0.81	0.80
	PBIAS (%)	-26.3	-5.1	-20.9	13.7	-5.9
	RSR	0.69	0.55	0.49	0.42	0.46
Monthly	Observed	12.6.1 (15.3)	19.5 (11.0)	24.0 (24.1)	26.2 (18.6)	20.8 (12.9)
	Predicted	9.3 (10.5)	18.5 (9.0)	19.0 (20.1)	29.8 (18.0)	19.6 (9.4)
	R^2	0.71	0.68	0.77	0.91	0.79
	NSE	0.63	0.67	0.73	0.87	0.75
	PBIAS (%)	-26.3	-5.1	-20.9	13.7	-5.9
	RSR	0.61	0.57	0.52	0.36	0.50

[a] Observed and predicted values are means (standard deviations in parentheses. RSR = ratio of the root mean square error to the standard deviation of observed data.

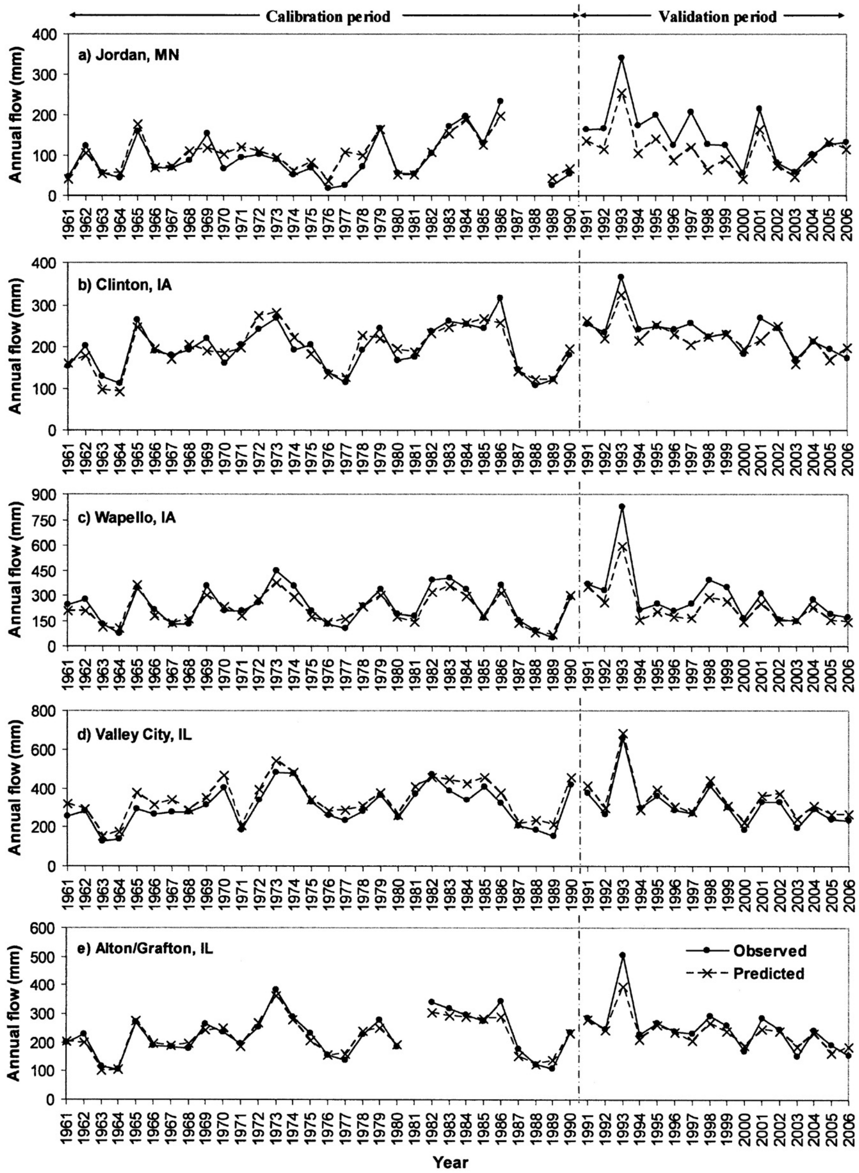


Figure 6. Observed and predicted annual streamflow for the upper Mississippi River basin.

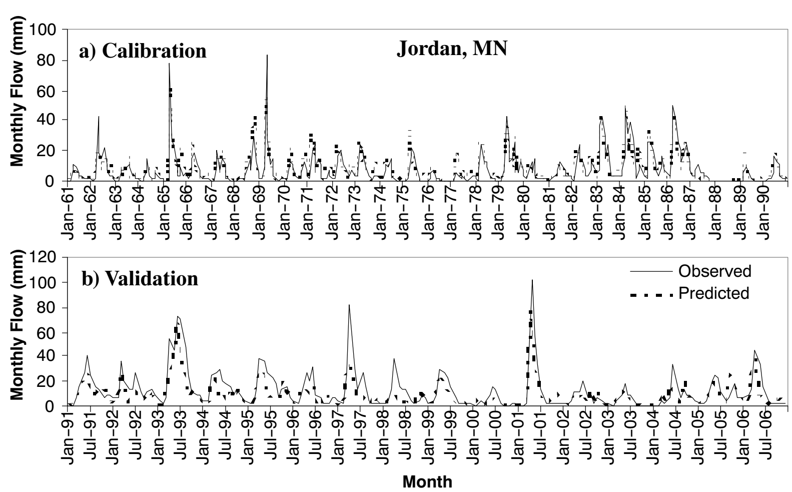


Figure 7. Observed and predicted monthly streamflow at the Jordan, Minnesota, station in the upper Mississippi River basin.

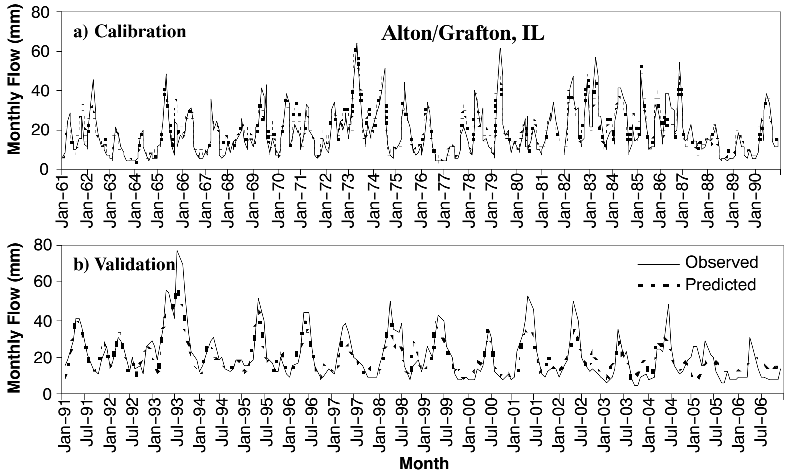


Figure 8. Observed and predicted monthly streamflow at the Alton/Grafton, Illinois, station in the upper Mississippi River basin.

and validation periods (fig. 6). However, annual streamflow on the Minnesota River at the Jordan, Minnesota, gauging station was clearly underpredicted in a few years during the validation period (fig. 6a). The modeling system underpredicted the peak flow during the validation period; however, overpredictions of peak flows were generally observed during the calibration period at the Jordan, Minnesota, gauging station (fig. 7). The monthly time series for the Alton/Grafton, Illinois, station are plotted in figure 8. In summary, the APEX and HUMUS/SWAT system reasonably captured the annual and monthly flow patterns in the UMRB.

Sediment Yield

Due to the large scale of this study and the separated simulations for cultivated and uncultivated lands, it is a challenge to use experimental data for validation of delivery ratios from edge-of-field to the 8-digit watershed outlet because the experimental watershed sediment data would include all source loads together. Therefore, we aimed to match available sediment data in order to have a modeling system adequate to perform scenario trials at the national scale. The average annual edge-of-field sediment loss from cultivated cropland with the current conservation condition in the UMRB is 2.09 t ha^{-1} (table 7). The average annual sediment load from cultivated cropland to the 8-digit watershed outlets in the UMRB is 18,597 thousand tons (0.72 t ha^{-1}) with the current conservation practices in use. The average annual sediment load from all uncultivated land to the 8-digit watershed outlets in the UMRB is 10,325 thousand tons (0.44 t ha^{-1}). The simulated total average annual edge-of-field sediment loss from all land use is 90,710 thousand tons. Not all of the sediment that leaves farm fields is delivered to streams and rivers. Some is bound up in various parts of the landscape during transport. In addition, instream degradation processes and streambed deposition and accumulation remove or trap a portion of the sediment delivered to streams and rivers. The simulated total average annual sediment delivered to the Mississippi River at Grafton, Illinois is 18,960 thousand tons (table 7). Based on the simulated average annual sediment loads at the various scales, the SDR from edge-of-field to 8-digit watershed outlets is 0.32, and the SDR from 8-digit watershed outlet through major streams and rivers to Grafton is 0.73 with the current conservation practices in place. Instream degradation has contributed to sediment loading; therefore, the sediment delivery is relatively increased.

Table 7. Simulated average annual sediment source loads from edge-of-fields and delivered to the 8-digit watershed outlets, and the instream sediment load in the upper Mississippi River basin (1960-2006).

		Cultivated Cropland[a] (257,026 km^2)		Uncultivated Land (234,669 km^2)		Total (491,695 km^2)[b]	
	Scenario	1000 ton	t ha^{-1}	1000 ton	t ha^{-1}	1000 ton	t ha^{-1}
Edge-of-field load	Current conditions	53,632	2.09	37,078	1.58	90,710	1.85
	No-practice scenario[c]	184,223	7.17	37,078	1.58	221,301	4.50
Delivered to 8-digit watershed outlet (t ha^{-1})	Current conditions	18,597	0.72	10,325	0.44	28,922	0.59
	No-practice scenario[c]	64,954	2.53	10,325	0.44	75,279	1.53
	Sediment reduction	71%		--		61%	
Delivered to Mississippi River at Grafton, Illinois	Current conditions	--		--		18,960	0.43
	No-practice scenario[c]	--		--		30,209	0.68
	Sediment reduction	--		--		37%	

[a] Cultivated cropland includes land in row crops or close-grown crops, hay and pasture in rotation with row crops and close-grown crops, and land in long-term conserving cover. The land enrolled in the general signup of the Conservation Reserve Program (CRP) was used to represent the long-term conserving cover.

[b] 444,183 km2 at Grafton, Illinois.

[c] No conservation practices, and the land in long-term conserving cover is cultivated with no conservation practices.

Since Walling (1983) pleaded for continuous research for increased understanding of the sediment delivery process in order to link onsite erosion to sediment yield at the basin outlet, there has been progress in spatially distributed modeling of soil erosion and sediment transport (de Vente et al., 2007). In addition, de Vente et al. (2007) acknowledged that high data requirements and the inability to consider all relevant erosion and sediment transport processes still hamper accurate prediction of sediment yield at the drainage basin scale using these models (Merritt et al., 2003; de Vente and Poesen, 2005). The current project is a study focused at the regional scale. Sediment yield at the 8-digit watershed level is estimated based on channel and watershed characteristics using the sediment delivery ratio equation in this study, although both APEX and SWAT are spatially distributed models with channel routing components. At the 8-digit watershed level, the channel routing feature is not used (except in APEX, while there are multiple subareas due to subdivision for conservation conditions). The inherent limitation of using SDR is the inability to account for stream channel erosion at the 8-digit watershed level. It is well known that channel erosion can contribute significantly to sediment load in some parts of the UMRB (Sekely et al., 2002; Thoma et al., 2005; Engstrom et al. 2009; Mulla and Sekely, 2009). For example, researchers have found that river bank erosion can contribute more than 40% of the sediment load in parts of the Minnesota River basin. Watersheds smaller than 8-digit watersheds should be studied in more detail in the future national study with the preparation of necessary data. In addition, the streambank and channel erosion component of the SWAT model and particle size distribution are under development (SWAT 2009 version). Currently, SWAT2005 is used for the CEAP assessment; once the necessary data required for the national model are prepared, those new developments will be included in the future modeling effort.

Without conservation practices, the model predicts that the average annual edge-of-field sediment loss from cultivated cropland would have been approximately 3.4 times higher that from the current condition. The SDR from the 8-digit watershed outlet through major streams and rivers to Grafton is 0.44 with no-practice conditions, which is much smaller than that under the current conservation conditions. With the conservation practices in place, overland flow has lower sediment concentrations. With more clear water than the no-practice conditions, it is expected that more sediment will be re-entrained from channels (higher flow energy) and the SDR will be higher than the no-practice scenario. Therefore, while implementing conservation practices on cultivated cropland, it is also necessary to have correspond–ing conservation practices in channels for maximizing potential gains.

The simulated annual sediment loads were compared with observed values at the Valley City and Alton/Grafton gauging stations (1986-2006). The simulated annual sediment yield matched well in trend and quantify to the observed values (fig. 9), with an NSE value of 0.88 at Valley City and 0.70 at Alton/Grafton. Although the modeling system shows promising results based on model performance statistics, it should be noted that uncertainties are associated with the data (e.g., channel dimensions, conditions of structural practices, measured data) and modeling limitations (e.g., neglect of streambank erosion at the 8-digit watershed level, the simplicity of SDR). Stream channel erosion and/or sediment deposition occur at the 8-digit watershed level. Therefore, both data updating and the development of an enhanced SWAT model with a streambank/channel erosion component and particle size distribution are underway for future national-scale modeling efforts. With consideration of streambank sediment sources from watersheds smaller than 8-digit watersheds, it is possible that the currently adjusted instream sediment-related parameters may need to be refined or recalibrated. While evaluating the benefits of conservation effects by comparing the relative differences between simulated current conditions (baseline) and no-practice conditions, the same set of instream sediment-related parameters would be used. Therefore, the simulated relative changes (downstream impacts) between baseline conditions and the no-practice scenario may not be significantly affected, although changing these parameter values and considering channel sediment sources would alter the absolute predictions and sources of contributions for both the baseline and no-practice scenarios. For this reason, when using absolute predictions, more consideration should be given to sources of uncertainties.

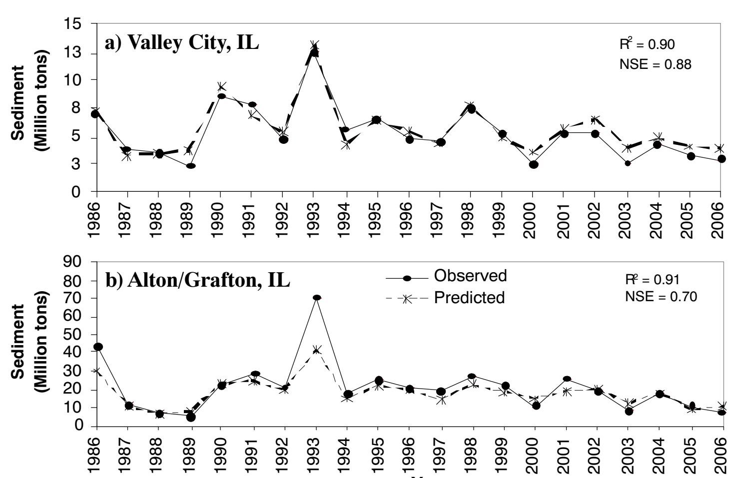


Figure 9. Observed and predicted annual sediment loads at (a) Valley City, Illinois, and (b) Alton/Grafton, Illinois, in the upper Mississippi River basin.

Table 8. Simulated average annual sediment source load and instream sediment load in the upper Mississippi River basin.

	Baseline Conservation Condition	Erosion Control on Critical Under-Treated Acres (15% of cropped acres)		Erosion Control on All Under-Treated Acres (62% of cropped acres)	
	Sediment Load (1000 ton)	Sediment Load (1000 ton)	Percent Reduction	Sediment Load (1000 ton)	Percent Reduction
Total at 8-digit watershed outlets (total area of 491,695 km^2 in UMRB)	29,030	21,772	25.0	15,694	45.9
Loads to Mississippi at Grafton, Illinois, 491,695 km^2 (total drainage area of 444,183 km^2)	18,960	16,964	10.3	15,241	19.3

The modeling approach was used for scenario analyses of alternative practices. In addition to the no-practice scenario for evaluating the benefits of current conservation practices, four alternative conservation treatment scenarios were used. Two scenarios for erosion control and two for nutrient management (see Assessment of Conservation Practices section) were simulated to evaluate the potential gains from further conservation treatment in the UMRB for the CEAP cropland national assessment (USDA-NRCS, 2010). For each scenario, only the conditions for cultivated cropland were changed; there was no change on uncultivated lands. Therefore, the edge-of-field sediment source loads from uncultivated lands are the same as shown in table 7. The current conservation practices have reduced sediment loss by 71% from cultivated cropland when compared to the no-practice scenario, and the total sediment reduction is 37% at Grafton, Illinois (table 7). The benefits of sediment reductions for the two erosion control scenarios, when compared to the current conservation conditions, are shown in table 8. Further erosion control of the critical under-treated acres (15% of cropped acres) (USDA-NRCS, 2010) could reduce the sediment yield by 10%. If all the under-treated acres (62% of cropped acres) were treated, sediment would be reduced by 19% at Grafton, Illinois (table 8). The simulations demonstrated that sediment losses could be effectively controlled in the region by treating the most vulnerable under-treated acres with additional erosion control practices. Detail discussion of the addition conservation treatments and the benefits on nutrient and pesticide losses can be found in USDA-NRCS (2010).

CONCLUSIONS

The CEAP cropland national assessment is intended to quantify the environmental effects of Farm Bill sponsored conservation programs. The combination of APEX for simulating cultivated cropland and HUMUS/SWAT for uncultivated land uses in the UMRB was used for this project. APEX simulations of conservation practices are briefly summarized in this study. The water yield calibration and the development of sediment delivery ratios were described. Simulated annual and monthly flows were in good agreement with observed values at five USGS gauging stations along the river basin, as evidenced by R^2 values of 0.66 to 0.94 and NSE values of 0.59 to 0.87 during the calibration period (1961-1990) and R^2 values of 0.68 to 0.98 and NSE values of 0.50 to 0.87 during the validation period (1991-2006). Simulated annual sediment loads compared well with observed values, with R^2 values of 0.90 and 0.91 and NSE values of 0.88 and 0.70 at the Valley City, Illinois, and Alton/Grafton, Illinois, gauging stations (1986-2006), respectively. Test results indicated the potential benefit of using the combined modeling system for large-scale studies and for performing scenario analyses to evaluate conservation practices.

The simulations provide comparisons between the baseline conservation condition and the no-practice scenario for assessing the effects of current conservation practices. Model simulations show that use of conservation practices has reduced instream sediment loads by 37% at the outlet of the UMRB at Grafton, Illinois. The model predicted sediment reductions of 10% and 19% at Grafton if additional conservation treatments for erosion control of the critical under-treated acres (15% of cropped acres) and for all the under-treated acres (62% of cropped acres), respectively, were performed.

It should be noted that the current study is focused at the regional scale. Although both APEX and SWAT are spatially distributed models with channel routing components, at the 8-digit watershed level the channel routing feature is not used (except in APEX, while there are multiple subareas due to subdivision for conservation conditions) because of the separated simulations for cultivated cropland (sample points) and uncultivated lands. The inherent limitation of using SDR is the inability to account for stream channel erosion at the 8-digit watershed level. Watersheds smaller than 8-digit watersheds should be studied in more detail in the future national study with the preparation of necessary data. The CEAP national cropland assessment is an ongoing research project, and development of SWAT 2009 is underway, which includes an improved streambank and channel erosion component and particle size distribution. Both new data preparation and new model development will be included in future national modeling efforts.

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